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**Mechanical function of vertebral body osteophytes,  
as revealed by experiments on cadaveric spines.**

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## Abstract

**Study Design.** Mechanical testing of cadaveric spines.

**Objective.** To determine if vertebral body osteophytes act primarily to reduce compressive stress on the intervertebral discs, or to stabilise the spine in bending.

**Summary of Background Data.** The mechanical significance of vertebral osteophytes is unclear.

**Methods.** Thoracolumbar spines were obtained from cadavers, aged 51-92 yrs, with vertebral body osteophytes, mostly antero-lateral. Twenty motion segments, from T5-6 to L3-4, were loaded in compression to 1.5 kN, and then in flexion, extension, and lateral bending to 10-25 Nm (depending on specimen size) with a compressive preload. Vertebral movements were tracked using an optical 2D MacReflex system. Tests were performed in random order, and were repeated following excision of all osteophytes. Osteophyte function was inferred from a) changes in the force or moment resisted, and b) changes in tangent stiffness, measured at maximum displacement or rotation angle. Volumetric bone mineral density (BMD) was measured using DXA and water immersion. Results were analysed using repeated measures ANOVA.

**Results.** Resistance to compression was reduced by an average 17% following osteophyte removal ( $p<0.05$ ), and resistance to bending moment in flexion, extension and left and right lateral bending was reduced by 49%, 36%, 36% and 35% respectively (all  $p<0.01$ ). Changes in tangent stiffness were similar. Osteophyte removal increased the neutral zone in bending ( $p<0.05$ ), and on average reduced motion segment BMD by 7-9%. Results were insensitive to applied loads and moments, but several changes were proportional to osteophyte size.

**Conclusions.** Vertebral body osteophytes resist bending movements more than compression. Because they reverse the instability in bending that can stimulate their formation, these osteophytes appear to be adaptive rather than degenerative. Results suggest that osteophytes could cause clinical BMD measurements to underestimate vertebral compressive strength.

## **Key Points**

1. Experiments on cadaveric thoracolumbar spines showed that removal of vertebral body osteophytes reduced motion segment resistance to compression by 17%, and resistance to bending moment by 35-49%.
2. Results suggest that vertebral body osteophytes primarily stabilize the spine in bending.
3. Osteophytes contribute only 7-9% of the BMD measurement for a motion segment, but they increase by 17% its ability to resist compression. This suggests that clinical BMD measurements will systematically underestimate vertebral compressive strength if osteophytes are present.

## **Précis**

Experiments on cadaveric thoracolumbar motion segments showed that vertebral body osteophytes resist an average 17% of applied compressive loading, but 35-49% of applied bending moments. Osteophyte growth can be stimulated by excessive bending movements, so their formation appears to be adaptive rather than degenerative.

## Introduction

Substantial osteophytes can be found on at least one vertebral body in 25% of spines aged 20-29 yrs, and in 90% of spines aged over 60 yrs.<sup>1</sup> They tend to be especially large on the antero-lateral margins, and are most common at lower cervical, lower thoracic, and mid-lumbar levels.<sup>1,2</sup> The word osteophyte (“bone-plant”) graphically portrays the branching microstructure of these osteo-cartilaginous outgrowths (**Figure 1**). Vertebral osteophytes typically grow by 4% per year in middle aged women.<sup>3</sup>

The mechanical significance of vertebral body osteophytes is unclear, although their occasional involvement in nerve entrapment syndromes<sup>1</sup> encourages clinicians to treat them as a degenerative condition,<sup>2,4</sup> sometimes grouped under the term “spondylosis”. They have been sub-divided into “traction” and “claw” spurs,<sup>5</sup> although these can co-exist on the same vertebra<sup>4</sup> and may simply represent early and late stages in a single process.<sup>1</sup> Osteophytes are associated with high compressive load-bearing by the spine<sup>2,6</sup>, with male gender,<sup>1,2</sup> with intervertebral disc degeneration<sup>2,3,7,8</sup> (though the association is not strong in elderly women<sup>9</sup>), and with Schmorl’s nodes<sup>10</sup> and endplate sclerosis<sup>8</sup>. There is a weak association with back pain.<sup>2,11</sup> Animal experiments have shown that scalpel-induced disc degeneration causes osteophytes to grow in adjacent vertebrae.<sup>12</sup> This same experiment concluded that osteophytes arise from proliferating annulus tissue which undergoes metaplasia into hyaline cartilage, and then ossifies in a manner similar to endochondral ossification in growth plates. Endochondral ossification has also been implicated in osteophyte formation at other skeletal sites.<sup>13</sup> Previous theories (summarised by Nathan<sup>1</sup>) suggested that vertebral osteophytes can arise from various tissues, including longitudinal ligaments and periosteum. Certainly, surgical disruption of these latter tissues in animals leads to rapid osteophyte growth on the underlying vertebra.<sup>14</sup>

Osteophytes can, however, be viewed in a more positive light. Bone growth in adults follows the principles of mechanically-adaptive remodelling, in which increases or decreases in stress cause alterations in bone strain (deformation) which are detected by osteocytes.<sup>15</sup> Osteoclasts and osteoblasts then remove or deposit bone until strain returns to normal levels.<sup>16</sup> This negative feedback arrangement is influenced by various factors, including a genetic predisposition to lay down more or less bone than normal,<sup>17</sup> and altered hormone levels which can stimulate formation or loss of bone, for example in women after the menopause. Nevertheless, the main purpose of new bone formation is to reduce excessive bone strain to normal levels. In the case of vertebral body osteophytes, this could be achieved by effectively increasing the cross-sectional area of the vertebral

body/disc unit, hence reducing the average compressive stress (force per unit area) acting on it. This could explain why vertebral osteophytes are associated with large body weight and high overall vertebral bone mineral density (BMD)<sup>9, 18</sup> and why they usually appear on the concave side of spinal curves, where the assumed compressive stresses are greatest.<sup>1</sup> Similarly, associations between early osteophyte formation and spinal instability could be explained by osteophytes forming in order to reduce movements and hence restore stability to a degenerated spinal level.<sup>19</sup> Eventual re-stabilisation could explain why only small developing osteophytes (sometimes characterised as traction spurs) are associated with instability.<sup>5</sup>

Whether osteophytes should be viewed as degeneration or adaptation depends on their mechanical function, and this is currently unknown. The present cadaveric experiment aims to quantify the function of vertebral body osteophytes in resisting bending and compression, in order to increase our understanding of their mechanical significance in the ageing spine. We also compare osteophyte function with measures of BMD, because BMD is often used to predict mechanical vulnerability in an ageing spine.

## Materials and Methods

*Cadaveric material.* Human thoraco-lumbar spines were removed within 72 hours of death from 11 cadavers (6 male, 5 female) aged 51-92 yrs (mean 77 yrs) which had radiographic evidence of vertebral body osteophytes. None of the subjects had died from a condition known to affect bone metabolism, or had experienced prolonged bed rest prior to death. Most osteophytes were antero-lateral, but some vertebrae had posterior osteophytes as well. Their length was measured from radiographs as shown in **Figure 2**, and an outgrowth was recognized as an osteophyte if its length exceeded 2 mm. The maximum length of any osteophyte from each motion segment was recorded. Spines were dissected into 20 “motion segments” (**Table 1**) consisting of two vertebrae and the intervening disc and ligaments, and subsequently stored at -20°C. All spinal levels between T5-T6 and L3-L4 were represented. All of the discs were degeneration grade 3 or more on a scale of 1-5<sup>20</sup>. Accordingly, grade of degeneration had little predictive value in the present experiment, and will not be considered further. Polythene film was used to minimise water loss from specimens during subsequent testing<sup>21</sup>.

*Mechanical testing apparatus* Each motion segment was secured in two cups of dental plaster so that compressive loading could be applied evenly to its outer surfaces. Loading was applied by a hydraulic materials testing machine (Dartec-Zwick-Roell, Stourbridge, U.K.). Two low-friction

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3 rollers of variable height (**Figure 3**) allowed compression to be applied to a specimen maintained at  
4 some constant angle of flexion or extension. If one of the rollers was removed, a combination of  
5 bending and compression was applied. Because the front roller was positioned approximately 30  
6 mm anterior to the geometric disc centre, a typical bending moment of 15 Nm could be achieved  
7 with a compressive load of 500 N. The use of this apparatus to simulate physiologically-reasonable  
8 loading has previously been justified.<sup>22</sup> An initial period of compressive creep loading (300 N for  
9 15 minutes) was applied in order to reduce post-mortem disc hydration to typical physiological  
10 levels.<sup>23</sup>

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12 *Resistance to compression* Each motion segment was positioned in 2-4° of flexion (depending on  
13 specimen mobility) in order to simulate the moderately flattened back typical of manual handling.<sup>24</sup>  
14 A few degrees of flexion is usually sufficient to remove compressive load-bearing from the neural  
15 arch, so that all of the load is resisted by the vertebral bodies and intervertebral disc.<sup>25</sup> The  
16 compressive force was then increased to approximately 1.5 kN, in a linear-ramp loading-unloading  
17 cycle that lasted 5.0 s, with the machine operating in “position-control” for maximum precision.  
18 The vertically-acting compressive force acting on the load cell, and the vertical ram displacement  
19 (Figure 3), were sampled at 100 Hz and plotted in real time on the computer monitor.

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21 *Resistance to bending* With the rear roller removed, a bending moment rising to 10-25 Nm  
22 (depending on specimen size and estimated strength) was applied and removed during a 5.0 s  
23 loading-unloading cycle under “position-control”. During this time the compressive force typically  
24 rose to a peak value of 400-900 N. Vertebral movements were tracked at 50 Hz using an optical 2-  
25 D MacReflex system which detected two reflective markers attached to the lateral cortex of each  
26 vertebral body and two more to each metal cup. Preliminary checks on each specimen were made to  
27 ensure that there was negligible movement between markers on the vertebrae and on the cups.  
28 Precision was better than 0.01 mm, errors in flexion/extension angles were less than 5%.<sup>22</sup> By  
29 rotating the upper plate and rollers about a vertical axis, bending tests were repeated in extension,  
30 and left and right lateral bending. The order of bending tests was randomized between specimens.

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32 *Creep loading* Resistance to compression and bending were measured before and after a 2 hr period  
33 of compressive creep loading at 1.0-1.5 kN (depending on specimen size). Creep loading expels  
34 water from the disc, so that post-creep results are applicable to the in-vivo situation after the 1<sup>st</sup> few  
35 hours of each day<sup>23</sup>. Creep also helps to ensure that subsequent bending moment-rotation graphs  
36 have good reproducibility<sup>22</sup>.

*Stress profilometry* After creep, distributions of compressive “stress” were measured along the mid-sagittal diameter of the intervertebral disc using a miniature pressure transducer, side-mounted in a 1.3 mm-diameter needle.<sup>26</sup> Stress profiles were obtained successfully from only two discs because the presence of osteophytes made the technique difficult, and transducer breakages were common.

*Removal of osteophytes* Tests were repeated following surgical excision of all osteophytes from the motion segment. Cutting was performed using a small saw and scalpel, as indicated in **Figure 4**. Removal of each bone fragment required an additional horizontal cut along the interface between vertebra and disc. The total volume of osteophytes removed from a given motion segment was measured using a water-displacement technique.

*Bone mineral density (BMD)* Before mechanical testing, the overall BMD of each motion segment was measured using dual photon X-ray absorptiometry (DXA) using a Piximus machine (Lunar Corporation, Madison, WI, USA) which has previously been calibrated against ash weight.<sup>27</sup> Measurements were performed with the radiation beam passing laterally through the specimen, and also with the beam passing in the antero-posterior direction, as occurs clinically. Volumetric BMD was measured for the removed osteophytes by scanning all removed fragments from a given motion segment, and then dividing the bone mineral content (BMC) by the total volume of the osteophytes, measured by water immersion.

*Statistical analysis* Repeated measures ANOVA was used to detect changes in mechanical properties after osteophyte excision. Linear regression was used to examine the influence of age and osteophyte size.

## Results

*Osteophyte resistance to compression* Sample force-deformation graphs in compression are shown in **Figure 5**. The graph for the intact specimen before creep loading served as a baseline, although the current paper concerns changes immediately before and after the removal of osteophytes. Osteophyte resistance to compression was analysed in two complementary ways. Firstly, the compressive force resisted at constant displacement (corresponding to a reference force before creep of 1000 N) was compared before and after osteophyte removal. For the example in Figure 5, the constant compressive displacement is 0.43 mm, as indicated by the vertical arrow. Osteophyte removal reduced the compressive force resisted by the motion segment, from 790 N to 610 N, so it can be inferred that the resistance coming from the osteophytes when in-situ was  $(790-610) = 180$  N, which is 23% of the resistance from the whole motion segment (790 N). This is a measure of the



osteophytes' *cumulative* resistance at all compressive loads up to 790 N. The second method involved comparing each motion segment's "tangent stiffness", before and after osteophyte removal. For the example in Figure 5, the tangent stiffness was evaluated as the gradient of the force-deformation graph, using 20 data points centered on the reference displacement of 0.43 mm, which corresponds to a force of 1 kN. Gradients are represented by oblique dotted lines in Figure 5. Any change in tangent stiffness after osteophyte removal provides a measure of the contribution of the osteophytes to resisting the *maximum* compressive force (790 N). This second measure of osteophyte resistance to compression is less sensitive than the first to any slight drift in zero displacement values during the experiment.

Average results are summarized in **Table 2** for both methods. Osteophyte removal reduced the motion segments' resistance to compression by an average 17-18%, depending on which method of analysis was used. High standard deviations probably reflect the varying size of osteophytes.

*Resistance to bending* Sample bending moment-rotation graphs are shown in **Figure 6**. Flexion and extension graphs were combined (as were graphs for lateral bending to left and right, which are not shown). Resistance to bending, measured at a reference moment of 5 Nm, was assessed using the same two methods as for compression, and average results for both methods are summarized in **Table 2**. Osteophyte removal reduced motion segment resistance to flexion by an average 49-50%, reduced resistance to extension by 36-42%, and reduced resistance to lateral bending by 35-41%.

*Influence of testing conditions on mechanical results* Osteophyte resistance to bending was additionally evaluated at a reference moment of 10 Nm in a sub-group of 6 specimens which appeared particularly strong and so were tested to higher moments. In this subgroup, reduction in resistance to flexion following osteophyte removal averaged 61% (SD 43%) at 5Nm, and 64% (SD 38%) at 10Nm. Equivalent values in extension were: 47% (SD 59%) at 5Nm, and 47% (SD 57%) at 10 Nm. The effect of osteophyte removal on resistance to small bending moments was investigated by evaluating the "neutral zone", which was defined as the range of flexion or extension in response to an applied bending moment of 0.5 Nm. Osteophyte removal increased the neutral zone in flexion from 1.1° (SD 0.8°) to 2.0° (SD 1.8°), and in right-sided bending from 2.4° (SD 0.8°) to 3.0° (SD 1.1°). Both of these increases were significant ( $p < 0.05$ ). Smaller non-significant increases in neutral zone were observed in extension and left-sided bending after osteophyte removal.

*Influence of osteophyte size on mechanical results* The length of the largest osteophyte removed from each specimen (Figure 2) averaged 7 mm (range 2-14 mm), and their combined volume

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3 averaged 1.47 cm<sup>3</sup> (SD 1.50 cm<sup>3</sup>, range 0.2 - 6.1 cm<sup>3</sup>). The mechanical influence of osteophytes  
4 generally increased with these measures of size, although there was considerable scatter. The  
5 strongest influence was between total volume (in cm<sup>3</sup>) of removed osteophyte, and decreased  
6 stiffness in right side bending ( $r^2=0.31$   $p<0.05$ ).  
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10 *Influence of BMD on mechanical results* Volumetric BMD of removed osteophytes averaged 0.37  
11 (SD 0.15) g/cm<sup>3</sup> and did not depend significantly on gender or age. It was a poor predictor of most  
12 mechanical outcomes, but was proportional to changes in compressive stiffness ( $r^2=0.34$ ,  $p<.05$ )  
13 and left sided bending ( $r^2=0.25$ ,  $p<0.05$ ) following osteophyte removal. Removal of all osteophytes  
14 reduced the BMD measurement for the whole motion segment by 7% (SD 5%) when BMD was  
15 measured in the sagittal plane, and by 9% (SD 13%) when BMD was measured in the antero-  
16 posterior direction.  
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24 *Stress profilometry* In both specimens, osteophyte removal reduced or removed a concentration of  
25 compressive stress in the adjacent annulus (**Figure 7**). These preliminary results are presented to  
26 stimulate future studies, perhaps using smaller transducers or mathematical modelling.  
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## 30 **Discussion**

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32 *Summary of findings* Vertebral body osteophytes resisted an average 17% of spinal compressive  
33 loading, and 35-49% of complex loading in bending and compression. Mechanical influences  
34 tended to increase with measures of osteophyte size, but were not sensitive to experimental  
35 conditions. Osteophyte removal reduced motion segment BMD by only 7-9% on average.  
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40 *Strengths and weaknesses of the study* Quantitative assessment of osteophyte function requires  
41 human specimens, and it took two years to collect the required 20 motion segments (with  
42 osteophytes) from donated human cadavers. A strength of the study is the method of testing, which  
43 aims to reproduce physiological-style complex loading as closely as possible, rather than to apply  
44 pure moments or forces. Motion segment resistance to bending and compression interact,<sup>28-30</sup> and  
45 few conditions in life would apply one without the other. Postmortem changes have little effect on  
46 the elastic mechanical properties of human spines.<sup>31,32</sup> Osteophyte removal necessitated cutting of  
47 some outer annulus fibres (Figure 4), so the observed mechanical effects are attributable to  
48 osteophytes and their attachments.  
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57 *Relationship to other studies* There is some experimental evidence that anterior osteophytes resist  
58 flexion more strongly than compression.<sup>33</sup> Cadaveric experiments have shown that disc  
59 degeneration leads to increased stress concentrations in the annulus fibrosus<sup>26</sup> and a finite-element  
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model has predicted that this can stimulate osteophyte formation.<sup>34</sup> Clinical studies of BMD have noted that vertebral body osteophytes are associated with increased vertebral BMD<sup>35</sup> and may explain why vertebral BMD often increases with age in men.<sup>36</sup>

*Explanation of results* The modest role of vertebral osteophytes in resisting compression can be attributed to the relatively high compressive stiffness of the human spine. Increasing the compressive force on a vertebral body-disc-vertebral body specimen from 250 N (equivalent to lying down) to 3 kN (equivalent to moderate manual labour) compresses the specimen by only 0.55 - 0.94 mm.<sup>37</sup> This small vertical deformation would be reduced further by the presence of neural arches, which can resist more than 50% of the compressive force on the spine when the discs are degenerated and narrowed.<sup>38</sup> Evidently, small compressive deformations of a fraction of a millimeter are not sufficient to produce substantial forces in vertebral osteophytes, even when they “bridge” adjacent vertebrae. This interpretation is supported by the finding that intra-discal nucleus pressure (which is a good indicator of overall disc compression) is not greatly affected by the presence of osteophytes (Figure 7) or by the presence of a spinal fixator<sup>39</sup> which would bridge adjacent vertebrae in a similar manner to bridging osteophytes. In both cases, vertical deformation of the mechanical linkage (bridging osteophyte, or instrumentation) is too small to generate much force within it.

None of the specimens in the present study had a complete and rigid anterior bridge of bone, so the influence of osteophytes on load-bearing must have come mainly from their ability to modify the resistance to deformation of the adjacent discs. If a disc is idealized as a circle in the transverse plane, then increasing its radius by 4 mm would typically increase its cross-sectional area by approximately 50%. Extremely large marginal osteophytes effectively increase disc area by this amount<sup>1</sup> and appear to remain bonded to the bulging disc; more typically, however, they increase disc area by 10-20%. This could explain why specimen resistance to compression fell by 17% in the present study when the osteophytes were removed.

The curving shape of many large osteophytes suggests that they also resist radial bulging by the disc. Radial bulging increases when discs lose height and internal pressure, rather in the manner of a flat tyre,<sup>40</sup> and this could explain why a pharmacological intervention that slows down disc space narrowing also slows down vertebral osteophyte growth.<sup>41</sup> Radial bulging is greater when the spine is subjected to bending compared to pure compression,<sup>42</sup> especially at high angles of bending<sup>43</sup> and this probably explains why osteophytes resist bending more than compression. Disc radial bulging tends to be greatest anteriorly,<sup>42</sup> especially after endplate fracture and disc decompression<sup>44</sup> and this

could explain why osteophytes tend to be larger anteriorly. Particularly high resistance to extension by anterior osteophytes (Table 2) can be explained by assuming the centre of rotation lies posterior to the disc<sup>22</sup> so that even small angles of extension stretch the calcified and fibrous tissues of the antero-lateral osteophytes.

If osteophytes do indeed represent adaptive remodelling, then they provide an interesting contrast with the generalised osteopaenia observed in most elderly spines. Why should bone be resorbed from vertebral body trabeculae, increasing the risk of osteoporotic fracture, if it is still possible for the vertebra to respond positively to mechanical stimuli by depositing bone in osteophytes?<sup>45</sup> New osteophyte bone may be denser than the rest of the vertebra<sup>1</sup> and this is supported by the present study, which reported average volumetric BMD of 0.37 g/cm<sup>3</sup> which is higher than the average values for vertebral bodies of similar age (0.17 g/cm<sup>3</sup>) measured previously on the same DXA machine.<sup>46</sup> Perhaps, the vertebral body margins are subjected to such high concentrations of stress that the resulting strains (deformations) exceed the threshold for bone deposition, even though the average stresses and strains on the vertebral body are much lower, and allow bone resorption?<sup>47</sup> High concentrations of compressive stress are applied to the vertebral margins by degenerated discs,<sup>26, 27</sup> and bulging discs will stretch the periosteum so that high tensile strains are generated where it inserts into bone.

*Unanswered questions and future research* Longitudinal studies on humans, or experiments on animals, are required to prove that motion segment instability is the primary stimulus for osteophyte formation. Similar studies could investigate whether osteophytes reduce in size as the motion segment regains stability following progressive fibrosis in the disc and ligaments.

*Clinical implications* Segmental instability follows disc degeneration<sup>22</sup> and appears to stimulate the growth of vertebral body osteophytes.<sup>12</sup> The present experiment shows that osteophytes act primarily to increase resistance to bending and to reduce the 'neutral zone' in bending. Therefore, osteophytes reverse the very stimulus that causes them to form. In this way, their growth can be viewed as purposeful, or adaptive, rather than degenerative.

A second clinical implication concerns BMD-based predictions of vertebral body compressive strength. The current findings suggest that BMD measurements systematically underestimate vertebral compressive strength if osteophytes are included. This is because the osteophytes contribute only 7-9% of the BMD measurement for a motion segment, but they increase by 17% its ability to resist compression. These cadaveric results therefore explain why a recent clinical study

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3 showed that BMD-based estimates of vertebral fracture risk are improved if “focal artifacts” such as  
4 osteophytes are excluded. <sup>48</sup>  
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**Table 1** Details of 20 motion segments tested from 11 cadaveric spines.

Gender	Age (yrs)	Motion segments	n
F	51	T6-T7 / T8-T9	2
F	67	T5-T6 / T7-T8/ T10-T11	3
M	84	L1-L2	1
M	74	T7-T8 / T9-T10	2
F	90	T8-T9 / T10-T11/ L1-L2/ L3-/4	4
F	76	T8-T9	1
F	92	T5-T6	1
M	82	T8-T9 / T11-T12	2
M	82	T12-L1 /T10-T11	2
M	82	T9-T10	1
M	72	T6-T7	1
Total number of motion segments			20

**Table 2** Changes in resistance to loading following osteophyte removal. Units of resistance to compression and bending are N, and Nm, respectively. Units of tangent stiffness are N/mm and Nm/deg respectively. Values represent the mean (standard deviation). Changes after osteophyte removal (AOR) are given as a %: all are significant (\* p<0.05, \*\* p<0.01).

	Resistance at constant displ./angle			Stiffness at constant displ./angle		
	Intact	AOR	% change	Intact	AOR	% change
Compression	803 (203)	664 (223)	-17 (22)*	2907 (997)	2406 (1081)	-18 (22)*
Flexion	4.02 (3.18)	1.70 (1.54)	-49 (39)**	4.15 (3.51)	1.67 (1.72)	-50 (39)**
Extension	4.62 (3.50)	3.02 (3.72)	-36 (51)**	5.86 (9.21)	1.25 (1.02)	-42 (52)**
R. lateral bend	2.91 (1.57)	1.76 (1.23)	-35 (42)**	2.24 (1.68)	1.15 (0.96)	-41 (34)**
L. lateral bend	2.91 (1.66)	1.65 (1.35)	-36 (46)**	2.03 (1.63)	1.17 (1.05)	-39 (32)**

## Figure Legends

**Figure 1** Micro-radiograph of a 2mm-thick section through a lumbar vertebral body, in the plane of the pedicle. There is a large antero-lateral osteophyte on the lower anterior margin, and smaller ones above and posteriorly. Note the concave upper endplate, which is indicative of osteopaenia.

(Reproduced from Adams et al.<sup>31</sup> with permission of the publisher.)

**Figure 2** Diagram of a vertebral body, anterior on left. The size of each osteophyte was calculated from sagittal-plane radiographs as the difference between the length of the line (8-3) and the line (1-3). The maximum size of any osteophyte on each motion segment was recorded.

**Figure 3** Apparatus used to apply compression and bending to each motion segment. The height of the posterior roller (on the right) could be adjusted to enable the specimen to be compressed while positioned in flexion or extension. Removal of one roller enabled the specimen to be tested in combined compression and bending. In stress profilometry, a pressure transducer was pulled through the loaded disc as shown.

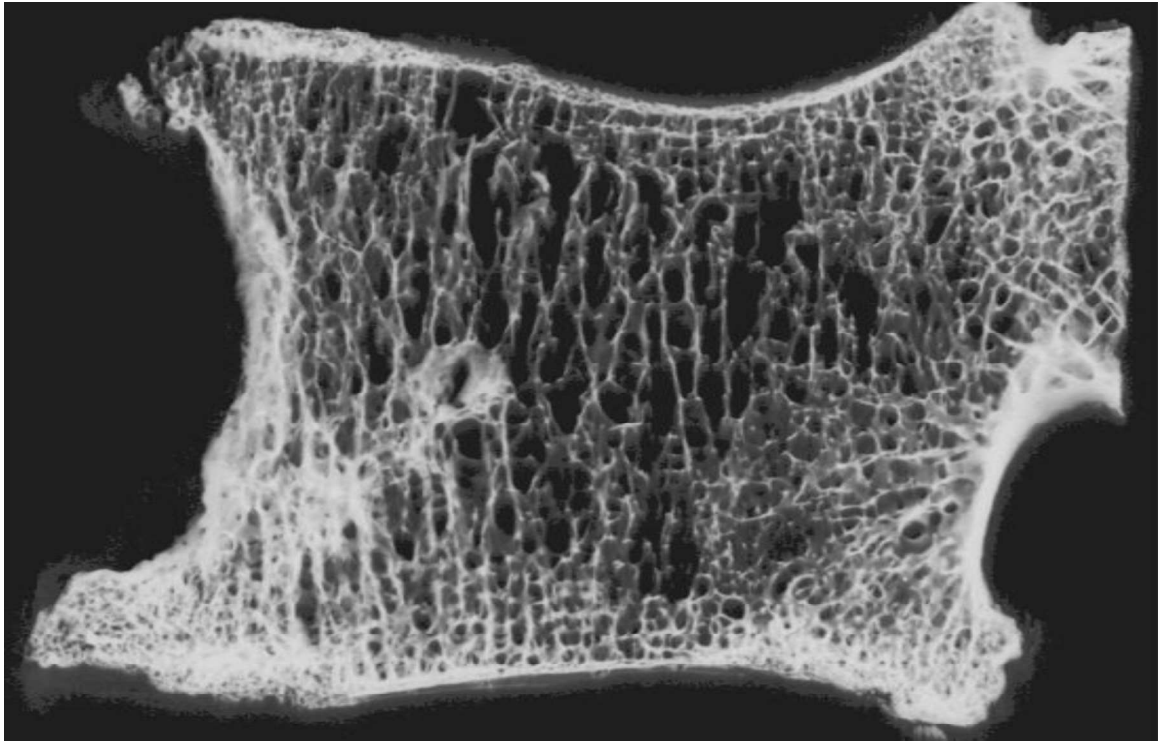
**Figure 4** Micro-radiograph of a 2 mm-thick mid-sagittal section through a lumbar vertebral body, showing two large anterior osteophytes. Osteophytes were surgically removed by cutting along the direction of the two arrows using a small saw, and then making horizontal cuts with a scalpel. This specimen also shows a Schmorl's node in its upper endplate. (Reproduced from Adams et al.<sup>31</sup> with permission of the publisher.)

**Figure 5** Compressive stiffness graphs for a typical motion segment, before creep (BC), after creep (AC) and after osteophyte removal (AOR). Resistance to compression (in N) was measured at the three points marked, at a constant displacement corresponding to an initial compressive force of 1000 N. Tangent stiffness (gradient of each graph) was measured (in N/mm) at the same three points. This specimen required a load of approx 100 N to flex the motion segment by 2-4 degrees, primarily against the resistance of intervertebral ligaments.

**Figure 6** Bending stiffness graphs for a typical motion segment, before creep (BC), after creep (AC) and after osteophyte removal (AOR). Responses in flexion and extension have been combined in the same graph. Resistance to flexion (in Nm) was measured at the three points marked, at a constant rotation angle corresponding to an applied moment of 5 Nm. Tangent stiffness (gradient of each graph) was measured (in Nm/deg) at the same three points.

**Figure 7** Distribution of vertically-acting compressive stress measured across the sagittal mid-line of an intervertebral disc, before creep (BC), after creep (AC) and after osteophyte removal (AOR).

(Anterior on right.) In this example, osteophyte removal appears to have reduced the peak compressive stress in the adjacent annulus.  $F_N$  = functional nucleus; IDP = intradiscal pressure.



## Figure 2

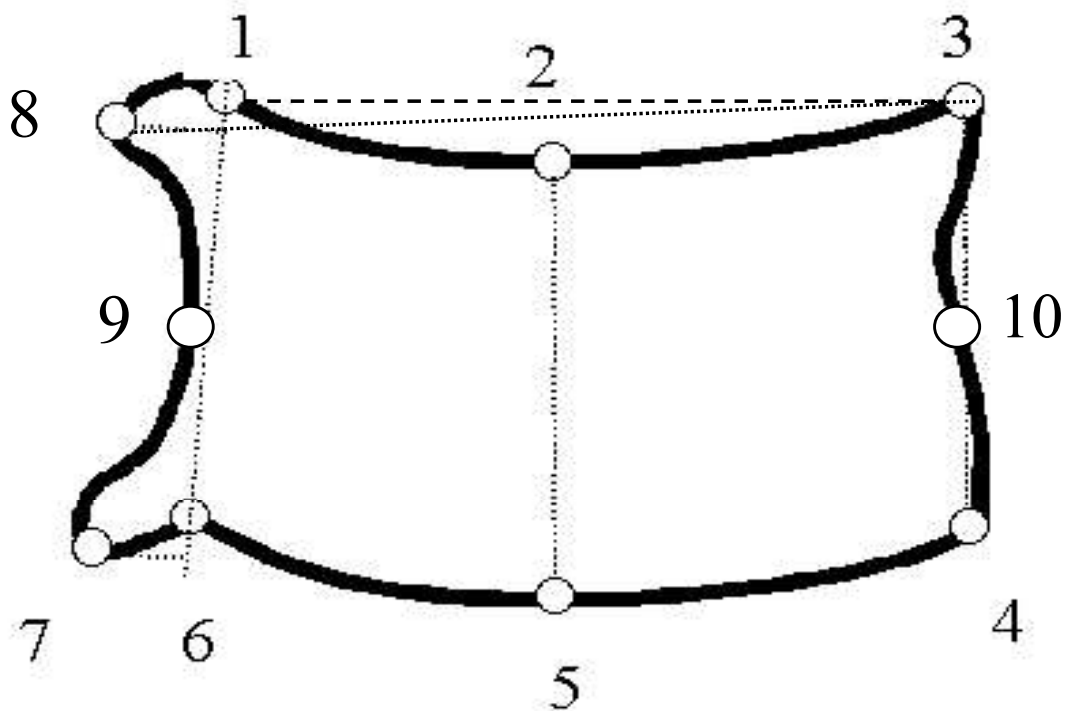


Figure 3

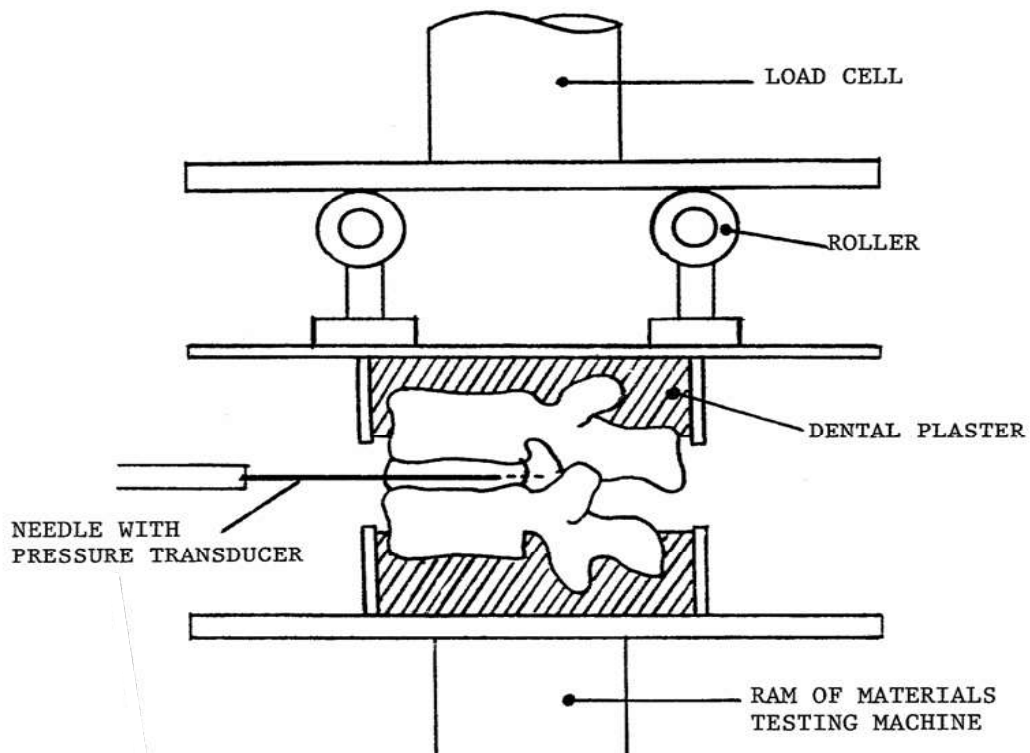
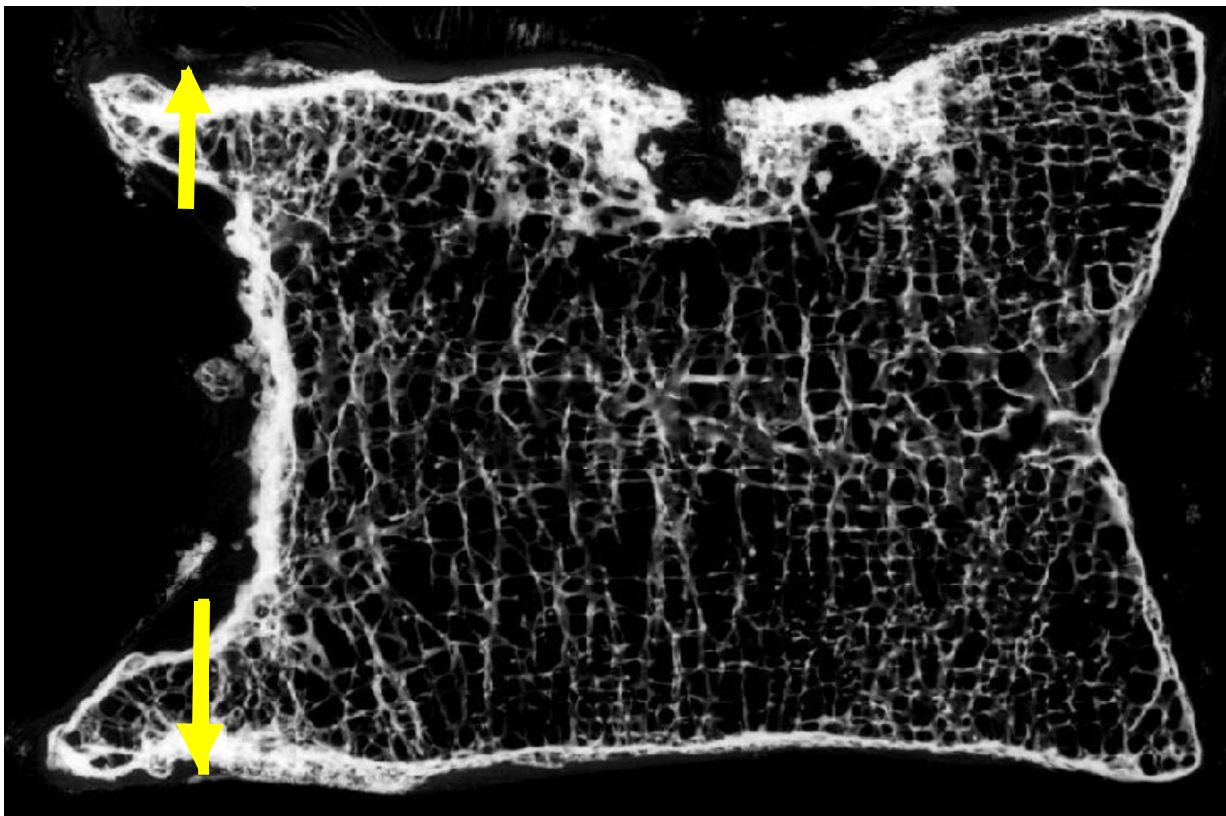
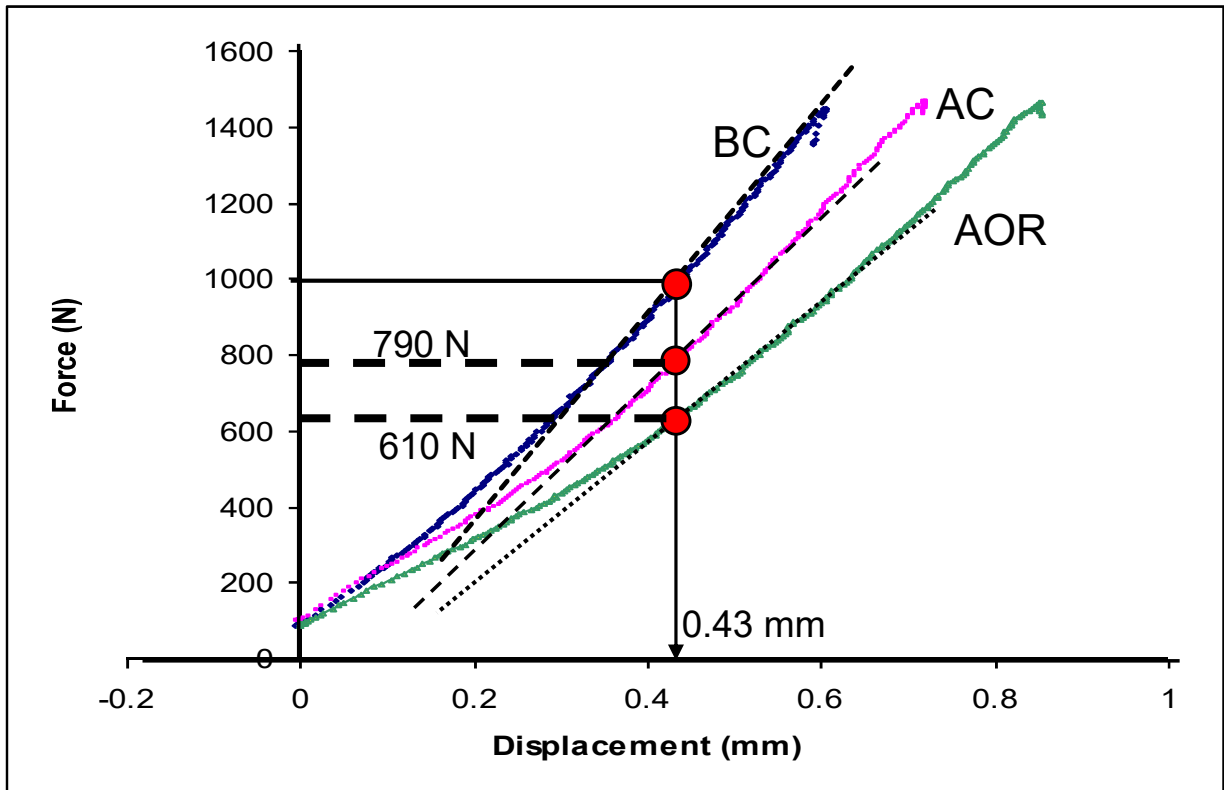


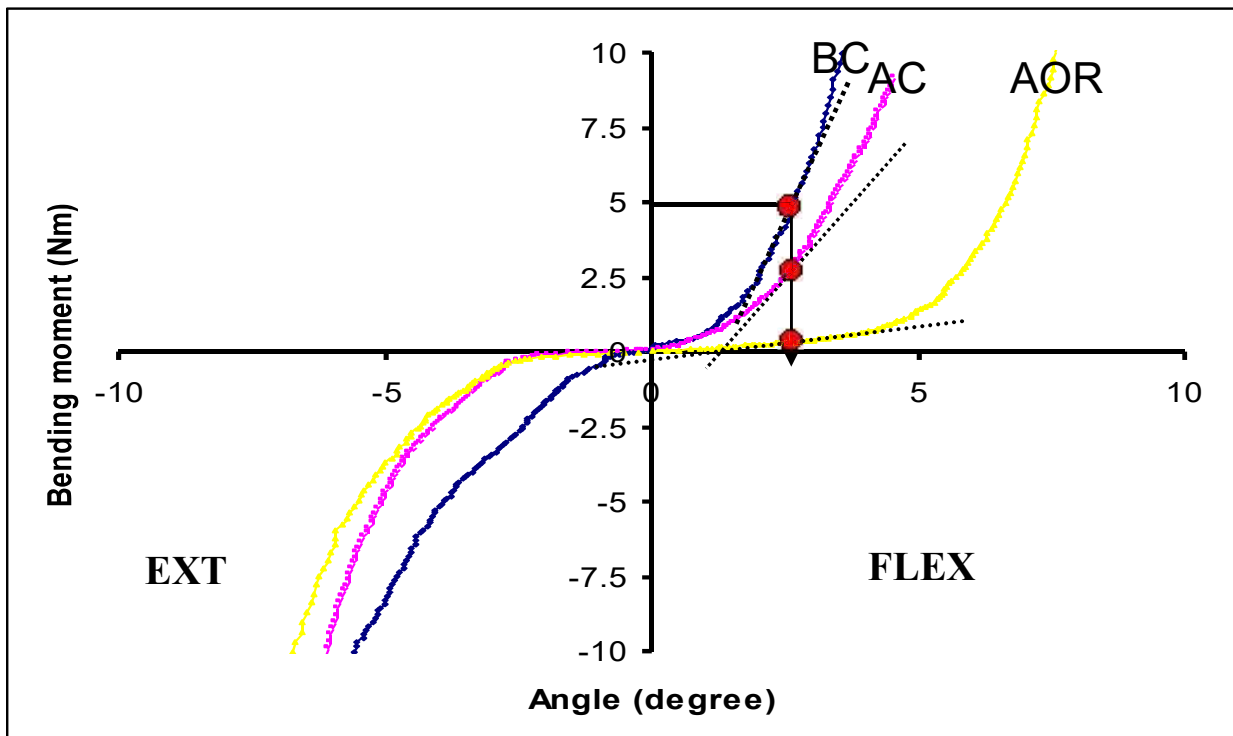
Figure 4



# Figure 5



# Figure 6



# Figure 7

